HELICOPTER HOGE CAPABILITY ASSESSMENT THROUGH CLIMATOLOGY MODELING

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July 2011

AMRDEC

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TRADE NAMES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01-05-2008	Special	May 2007 - May 2008

4. TITLE AND SUBTITLE

Helicopter HOGE Capability Assessment through Climatology Modeling

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

United States Army Research, Development and Engineering Command
Attn.: RDMR-AE
Bldg. 4488
Redstone Arsenal, AL 35898-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

Presented at the American Helicopter Society 64thAnnual Forum, Montréal, Canada, April 29 -May 1, 2008.

14. ABSTRACT

This paper presents an updated examination of the United States Army's hover out of ground effect performance criterion for helicopters. This requirement has been the subject of controversy since its initial issue during the 1950s due to cost and weight constraints in a helicopter's design. Over the succeeding years, various studies produced contradictory recommendations as to the most appropriate temperature and altitude combination for use in specifying global helicopter operational capability. Modern climate models can provide data for a greater number of locations around the world than was available in the past. By coupling this data with a helicopter's design point performance, it is possible to visualize a helicopter's operational capability in terms of worldwide distribution of temperature and pressure altitude mean averages and extremes. It is thus possible to graphically understand the design trade space and to tailor the helicopter's operational capability for specific geographic regions.

15. SUBJECT TERMS

HELICOPTERS, HOVER, DESIGN POINT, OPERATIONS, ALTITUDE, TEMPERATURE, CLIMATE

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	Same as Report (SAR)	11	19b. TELEPHONE NUMBER *(Include area code)*
unclassified	unclassified	unclassified			

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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This paper presents an updated examination of the United States Army's hover out of ground effect performance criterion for helicopters. This requirement has been the subject of controversy since its initial issue during the 1950s due to cost and weight constraints in a helicopter's design. Over the succeeding years, various studies produced contradictory recommendations as to the most appropriate temperature and altitude combination for use in specifying global helicopter operational capability. Modern climate models can provide data for a greater number of locations around the world than was available in the past. By coupling this data with a helicopter's design point performance, it is possible to visualize a helicopter's operational capability in terms of worldwide distribution of temperature and pressure altitude mean averages and extremes. It is thus possible to graphically understand the design trade space and to tailor the helicopter's operational capability for specific geographic regions.

Introduction

The vertical flight capability of helicopters is one of the most important performance parameters for U.S. Army acquisition programs. The specific atmospheric condition used to quantify this requirement has been the subject of debate for almost as long as helicopters have been in service. The atmospheric design point is expected to be representative of worldwide geographical regions where the Army is likely to operate during a helicopter's operational life. However, designing for extreme climatic conditions can result in increased weight and cost of the helicopter.

In the 1950s, the U.S. Army promulgated a requirement that future Army helicopters should be capable of Hover Out of Ground effect (HOGE) at a pressure altitude of 6,000 feet and an ambient temperature of 95 degrees Fahrenheit (6K/95). This condition was more stringent than the Air Force and Navy HOGE requirement of 6,000 feet pressure altitude and 81 degrees Fahrenheit ambient temperature, and would roughly double the air frame weight to meet this requirement. The Army Quartermaster Research and Engineering Center was tasked to conduct a study of the geographical implications of the difference between the two design points (Ref. 1). Dodd examined the probability of occurrence of hot temperatures for geophysical elevations between 1 and 2 kilometers and latitudes between 45° N and 45° S. He found a significant global distribution of highlands within these criteria that would exceed the Army 6K/95 design point, especially in areas of strategic and operational interest within southern Asia and North America, including the western United States.

In 1968, the United States Army Combat Developments Command (CDC) released results of a study on vertical flight performance criteria for Army helicopters (Ref. 2). This study was motivated by two previous studies. In 1964, Boeing-Vertol performed a study of hover capabilities over areas of the world where military helicopters were most likely to be used. This region was defined as being within 1,500 nautical miles of the equator and excluded areas that could be serviced by fixed-wing aircraft or land vehicles. It was concluded that helicopters designed to the 6K/95 point would have an 87 percent cumulative probability of HOGE in the included areas during the hottest month. In 1965, the Combat Operations Research Group (CORG) released the results of a study of the Army hover design criteria as related to the Utility/Tactical Transport Aircraft requirements formulation. This study focused on geopolitical regions contiguous to Soviet-Sino Bloc nations, and used geographical area to weight the probability of hot temperature occurrence. Based upon this analysis, the CORG argued that a HOGE design point of 4,000 feet pressure altitude and 95° Fahrenheit ambient temperature would capture 95 percent of the most probable altitude/ temperature combinations.

The CDC study argued that the motivation behind these two studies was faulty. Military helicopters had to be capable of performing other maneuvers besides HOGE in a combat zone. Also, mechanical degradation from system operation would impose additional constraints on helicopter performance over their operational life. The CDC study recommended a design point of 4,000 feet pressure altitude, 95° Fahrenheit ambient temperature, and a 500 feet per minute Vertical Rate of Climb (VROC) requirement with a 5 percent power margin.

In 1970, Bellaire and Bousman reexamined the Army Hot Day hover design criterion as it related to parametric helicopter design (Refs. 3,4). Using geophysical elevation and mean maximum daily temperature data, they developed graphs of cumulative probability distribution of elevation and cumulative probability distributions of temperature at elevation that could be used to graphically calculate a helicopter's cumulative probability of HOGE for a given geographical region. After studying nineteen countries contiguous or near to Soviet-Sino geopolitical block nations, they concluded that there was no single, optimum temperature/pressure altitude design point criterion for rotorcraft, but that a range of design points could be specified. Based upon this analysis, various Army helicopter acquisition programs selected the 4K/95 HOGE design point, others opted for the original 6K/95 design point, and

still others selected the 4K/95 with VROC and maneuverability requirement design point.

Horacek and Calvert evaluated HOGE capability as a function of monthly mean maximum, mean average and mean minimum temperature from data calculated by modern climatology models at the U.S. Air Force Combat Climatology Center (Ref. 5). A HOGE ceiling was defined as a function of pressure altitude and ambient temperature. The HOGE performance data used to define the curve was representative of helicopters developed during the late 1960s / early 1970s. This HOGE ceiling was used to create maps showing monthly probability of HOGE capability over a given region. It was found that the monthly HOGE capability could vary significantly for a given region during the year.

Horacek and Calvert expanded the work done in their previous paper by considering changes in effective pressure altitude due to monthly variations in local atmospheric pressures (Ref. 6). Mean maximum, mean minimum and mean average pressure altitudes were used in combination with mean maximum, mean minimum and mean average temperatures to calculate monthly HOGE capabilities for a given region. They found wide variation in the probability of HOGE estimates, which depended on which temperature/pressure altitude combination was used in evaluating geographical performance.

The earliest efforts to define a design point for helicopter HOGE performance assumed equivalence between geophysical elevation and pressure altitude. Later investigations focused on comparing HOGE capability as a function of mean minimum, average and maximum temperature/pressure altitude combinations. These papers have presented an array of different temperature and pressure altitude/ elevation combinations that require independent judgment as to the particular temperature/pressure altitude combination for use in evaluating operational capability. A consolidated approach would eliminate uncertainty from choosing among the various combinations. The focus of this paper is on the ability to combine mean minimum, average and maximum pressure altitude data into consolidated graphs and charts for use in evaluating HOGE performance.

Probability of Atmospheric Conditions

Modern numerical models combined with high performance computing resources can calculate time variant meteorological data for areas of interest throughout the world. The climatology data used in this investigation was provided by the U.S. Air Force Combat Climatology Center's Advanced Climate Modeling and Environmental Simulations (ACMES)

project (Ref. 7). ACMES assimilated sparse meteorological observations into a mesoscale numerical model to calculate meteorological data on a 40 kilometer grid. From this 40 kilometer grid solution, ACMES interpolated mean maximum, average, and minimum temperatures and pressures as a function of longitude, latitude and elevation for a 10 kilometer grid. Geophysical elevations used for the 10 kilometer grid were taken from satellite data with a grid resolution of 1 kilometer.

The monthly mean minimum and mean maximum values for temperature and pressure are simple averages of the daily extremes for temperature and pressure for a given month at a given location. The monthly mean average temperature and pressure values are simple averages of all temperatures and pressures readings for a given month at a specific location. However, there is no physical basis that guarantees that mean average values will be equal to the simple average of the mean minimum and mean maximum values for temperature and pressure. Therefore, the mean average temperature and pressure values can be taken as central weighting values for the most common extremes denoted by the mean maximum and mean minimum values.

Through use of the U.S. Standard Atmosphere Model (Ref. 8), it is possible to calculate an equivalent pressure altitude for a given pressure and temperature. Figure 1 is a cumulative probability plot (Ref. 9) of the cumulative distributions of ambient temperature (CPT) and equivalent pressure altitude (CPH$_P$) occurrences for Afghanistan. Afghanistan was chosen for illustration due to its large variations in elevation and temperature. The
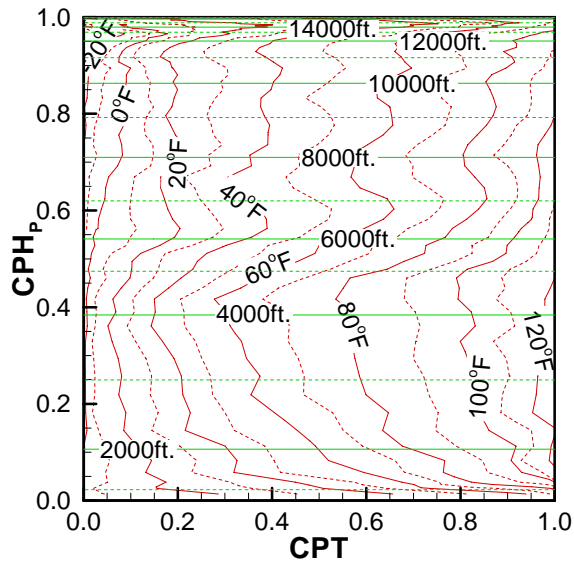
cumulative distribution of pressure altitude occurrence is plotted against the y axis and is denoted by the green contours. The cumulative distribution of temperature occurrence at a given pressure altitude is plotted against the x axis and is denoted by the red contours. As may be seen from the figure, the temperature distribution varies as a function of pressure altitude.

The pressure altitude contours shown on the plot were calculated numerically. The twelve monthly ACMES datasets were combined and the pressure altitude data was scanned for the least and greatest values. The minimum to maximum pressure altitude range was then partitioned into intervals. The sizes of the intervals were typically determined by the separation of pressure altitude occurrences at the elevation limits, and by the delta in pressure altitude that would minimize small scale oscillations in the final graph contours. The probability of pressure altitude occurrences were then calculated by dividing the total number of data points equal to or lower than the upper bound for a given interval by the total number of points in the region.

The temperature contours shown on the graph were determined in a similar fashion. The maximum and minimum temperatures were determined for each pressure altitude interval. The ranges between the minimum and maximum temperatures were then subdivided into equal intervals. The sizes of the intervals were typically determined by the distribution of the temperature values. The probability of temperature occurrences were then calculated by dividing the total number of data points equal to or lower than the upper bound for a given
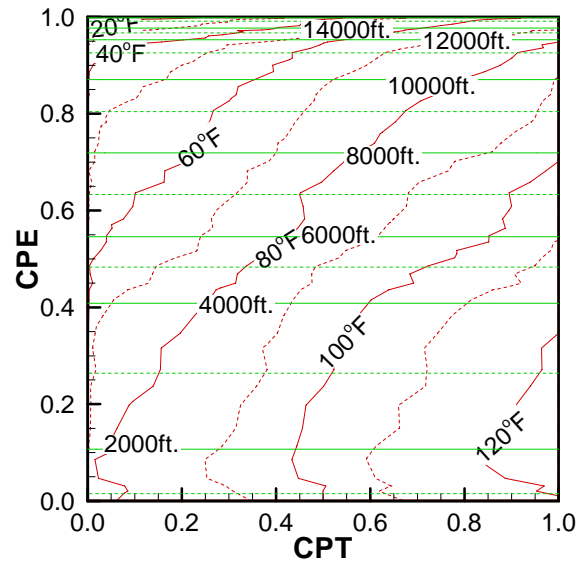

Figure 1: Cumulative probability of combined equivalent pressure altitude and temperature occurrences for Afghanistan.

Figure 2: Cumulative probability of geophysical elevation and mean maximum temperature occurrences for Afghanistan.

temperature interval by the total number of points lying within the specified pressure altitude interval.

For comparison to the methodology suggested by Bousman (Refs. 3,4), Figure 2 shows a graph of the cumulative distributions of mean maximum ambient temperature and geophysical elevation (CPE) occurrences for Afghanistan. By comparing the graphs, it may be noted that equivalent pressure altitude contours occur at slightly lower cumulative probabilities than those of geophysical elevation. This indicates that equivalent pressure altitude is biased slightly higher than geophysical elevation at a large number of locations in Afghanistan. The magnitude of bias is not uniform across the range of geophysical elevations shown.

By including the mean maximum, average and minimum temperatures in Figure 1, it is possible to estimate the true probability of temperature occurrence during a given year at each pressure altitude occurrence. In Figure 2, the hottest temperatures are overemphasized, giving a distorted view of the climate for the region under examination.

Annual Cumulative Probability of HOGE

A helicopter's hover capability is significantly influenced by the atmosphere in which it operates. The density of air is proportional to pressure and inversely proportional to temperature. Compressibility effects are inversely proportional to the square root of the temperature of ambient air. Both compressibility effects and air density combine to determine the amount of work that a rotor has to accomplish to create thrust.

The hover ceiling for a helicopter at a given gross weight may be defined in terms of altitude and temperature (Ref. 10). As an example, the HOGE ceiling for a helicopter representative of those designed during the late 1960s/ early 1970's is plotted on Figure 3. For comparison purposes, Figure 4 shows the same HOGE ceiling plotted on the mean maxim temperature, geophysical elevation graph.

Bousman (Ref. 11) used the HOGE curves plotted on the graphs to graphically calculate the probability of HOGE. The probability of HOGE was calculated by dividing the area under the HOGE curve by the total area of the graph. While this is still a viable methodology, it is possible to calculate the probability of HOGE via Monte Carlo integration (Ref. 12). Each individual point in the plot represents an elemental area of equal size to the others. By counting up the number of points lying under the curve, and dividing by the total number of points contained in the graph, it is possible to numerically calculate the annual cumulative probability of

HOGE. The accuracy of the estimate is dependent upon the size of the elemental area represented by each data point, with the accuracy increasing with decreasing elemental area size.

The Monte Carlo method described above was used to calculate the annual probabilities of HOGE for Figures 3 and 4. The annual probability of HOGE from the combined temperature and pressure altitude data plot shown in Figure 3 was calculated as 75 percent. The annual probability of HOGE obtained
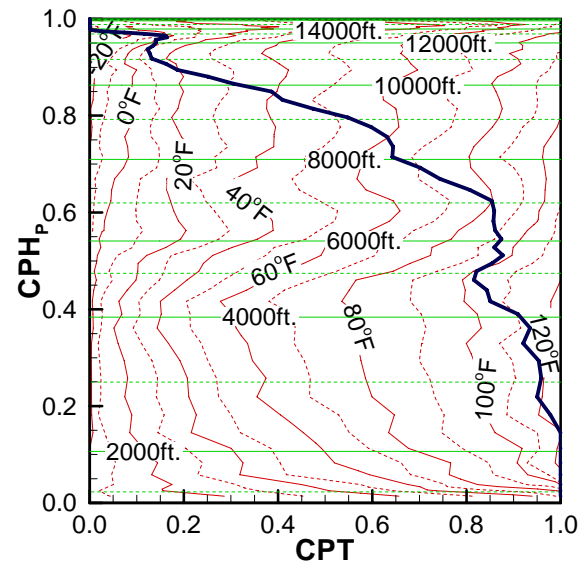

Figure 3: Hover performance ceiling for Afghanistan, based upon combined temperature and equivalent pressure altitude data.
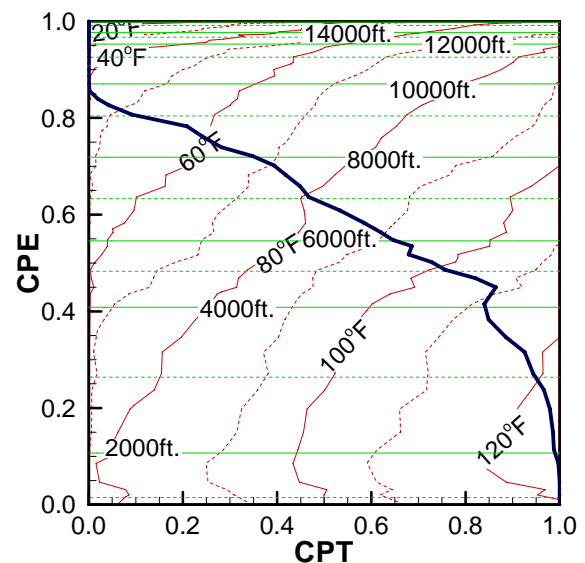

Figure 4: Hover performance ceiling for Afghanistan, based upon mean maximum temperature and geophysical elevation data.

by using mean maximum temperatures and geophysical elevations shown in Figure 4 was found to be 61 percent. Thus, the Bousman approach yields a more conservative estimate for annual HOGE probability than the methodology presented here by ignoring fluctuations in temperature. This is somewhat mitigated by ignoring fluctuations of pressure altitude from geophysical elevation.

Monthly Geographical Probability of HOGE

The annual cumulative probability of HOGE plots shown previously provides a single number when considering HOGE capability for selected regions of the world. They do not provide any details on HOGE capabilities within the regions during the year, however. It is feasible to partition the region into smaller areas and time intervals and to create additional cumulative probability plots for the partitioned areas and times. This would have the disadvantage of quickly becoming unwieldy due to the large number of plots that would be required for global operations.

A second alternative that is presented here used the power of modern personal computers to post process the ACMES output to create maps of helicopter HOGE capability. Each data point location has temperature and altitude data associated with it. Two methodologies were used to process this data. The first used mean minimum, maximum and average temperature and pressure altitude data to calculate probabilities of HOGE for each data point location. In the second method, geophysical elevation was used in place of the pressure altitude data for calculating HOGE capability.

Due to a lack of a significant correlation between temperature and pressure, the minimum probability of HOGE is obtained by using the mean maximum equivalent pressure altitude data with the mean maximum temperature value data to calculate the possibility of HOGE. The maximum probability of HOGE is calculated by using the mean minimum equivalent pressure altitude data with the mean minimum temperature value. These combinations therefore represent the most extreme conditions likely to be encountered at a location.

Odd numbered Figures 5 through 27 show the example helicopter's monthly capability maps for Afghanistan where combined pressure altitude and temperature data was used to calculate HOGE potential. Even numbered Figures 6 through 28 show corresponding HOGE capability maps where geophysical elevation was used in place of pressure altitude data in calculating HOGE capability. The red areas represent regions where the probability of HOGE is virtually zero. These are locations where the mean minimum temperature and altitude exceeds the HOGE ceiling boundary. The burnt orange areas are locations where probability of HOGE is between 0 and 50 percent. In these locations the mean average temperature and altitude exceed the HOGE ceiling boundary, but the mean minimum temperature and altitude does not. The yellow areas are locations where the probability of HOGE is between 50 and 100 percent. In these locations the mean maximum temperature and altitude exceeds the HOGE ceiling boundary, but the mean average temperature and altitude does not. The green areas represent areas where the probability of HOGE capability is virtually assured. In these regions, the mean maximum temperature and altitude lie within the HOGE ceiling curve.

Table 1 shows the cumulative probabilities of HOGE for each month from Figures 5 through 28.
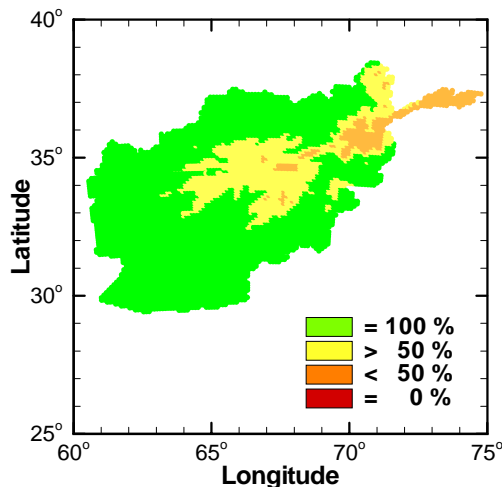

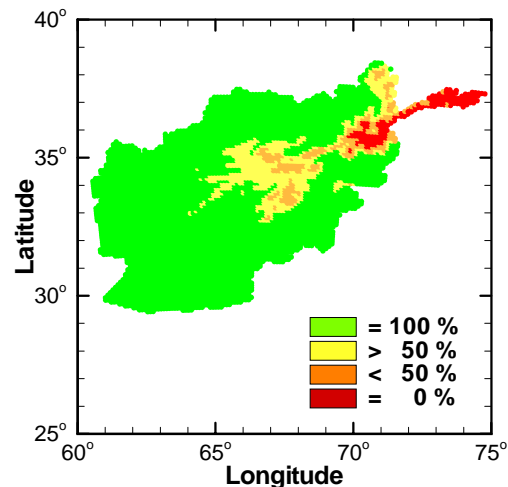**Figure 5: HOGE capability for January, based upon equivalent pressure altitude.**

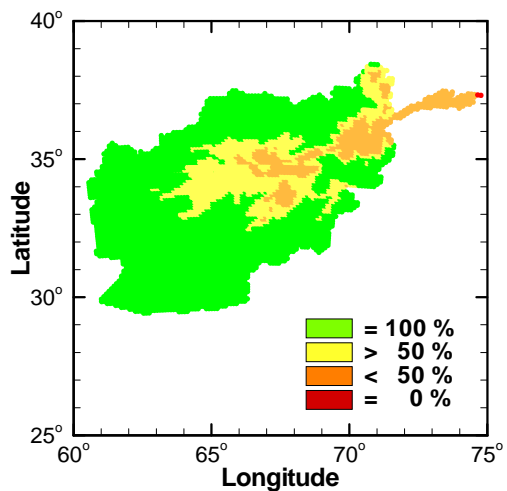**Figure 6: HOGE capability for January, based upon geophysical elevation.**

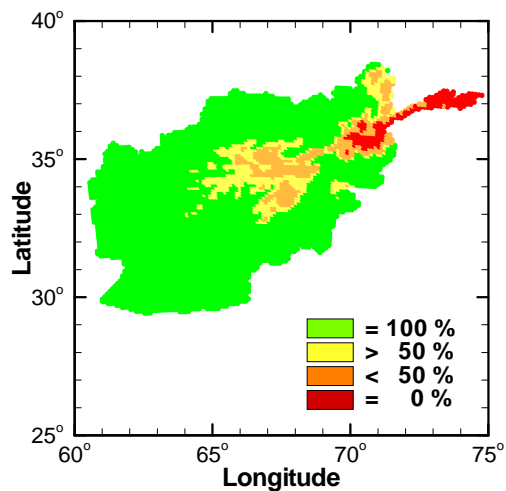**Figure 7: HOGE capability for February, based upon equivalent pressure altitude.**

Figure 10: HOGE capability for February, based upon geophysical elevation.
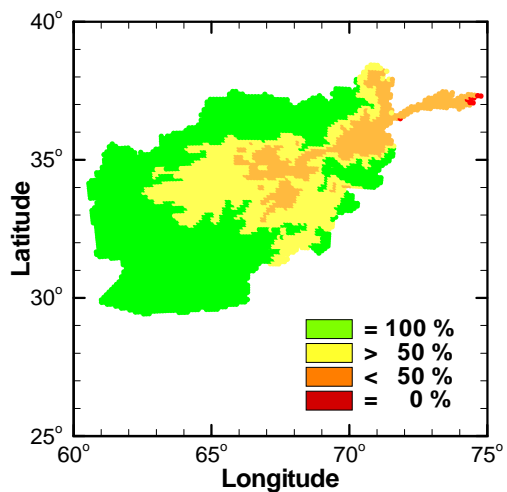

Figure 8: HOGE capability for March, based upon equivalent pressure altitude.
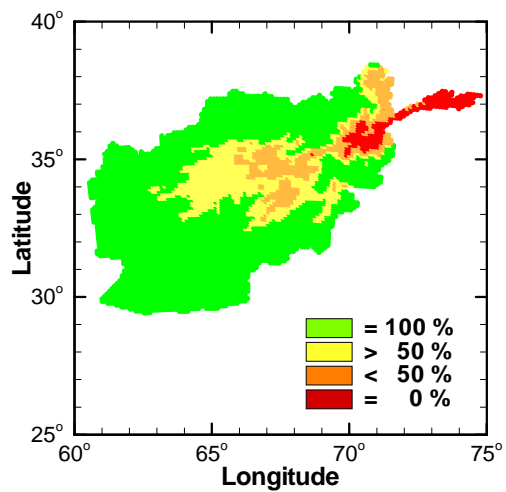

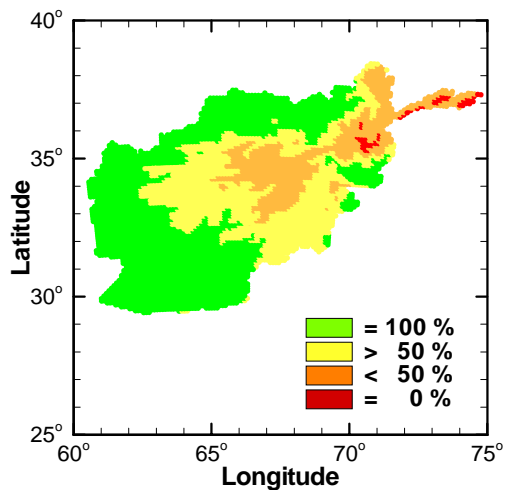**Figure 11: HOGE capability for March, based upon geophysical elevation.**

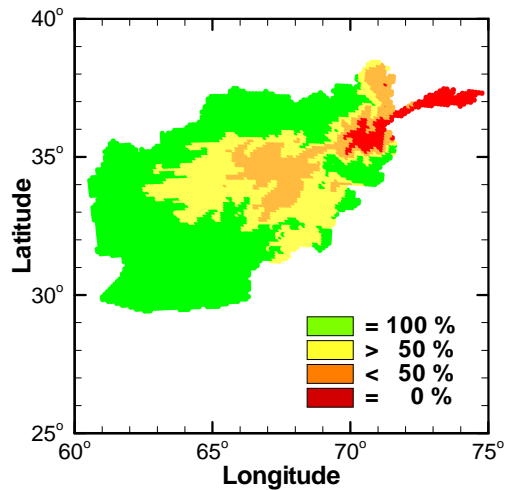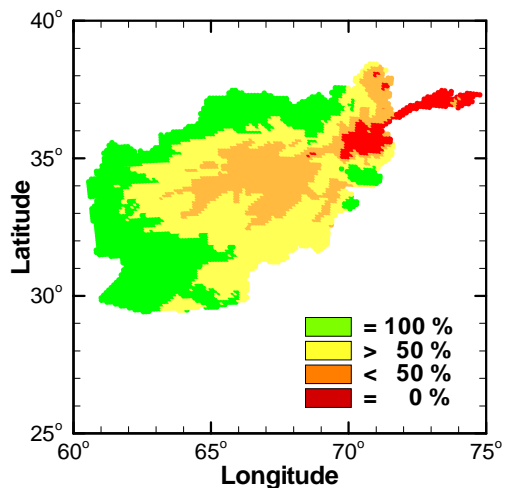**Figure 9: HOGE capability for April, based upon equivalent pressure altitude.**

Figure 12: HOGE capability for April, based upon geophysical elevation.

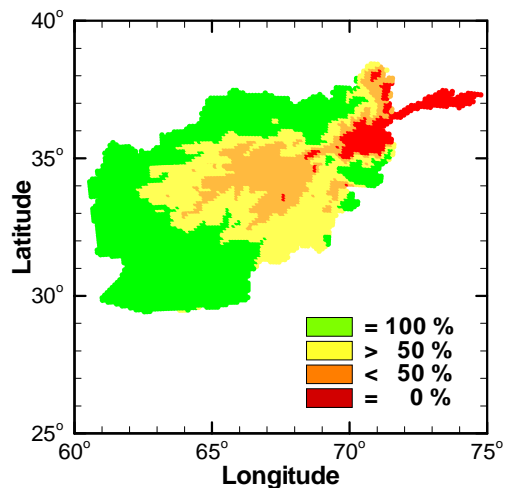**Figure 13: HOGE capability for May, based upon equivalent pressure altitude.**

Figure 16: HOGE capability for May, based upon geophysical elevation.
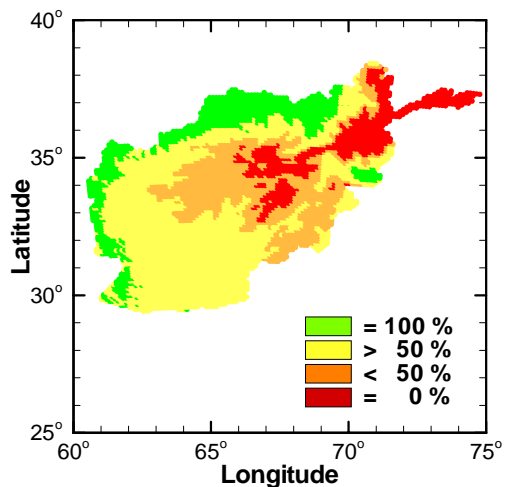

Figure 14: HOGE capability for June, based upon equivalent pressure altitude.
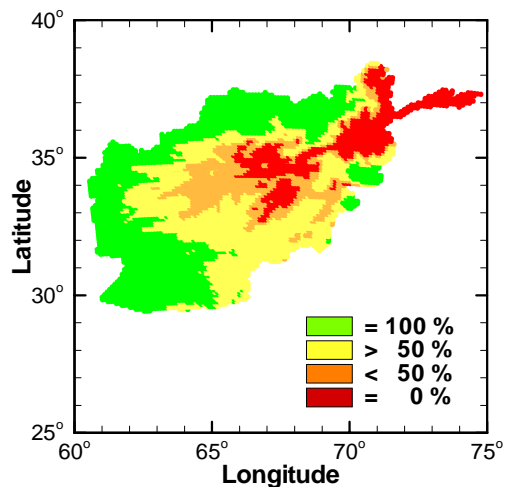

Figure 17: HOGE capability for June, based upon geophysical elevation.
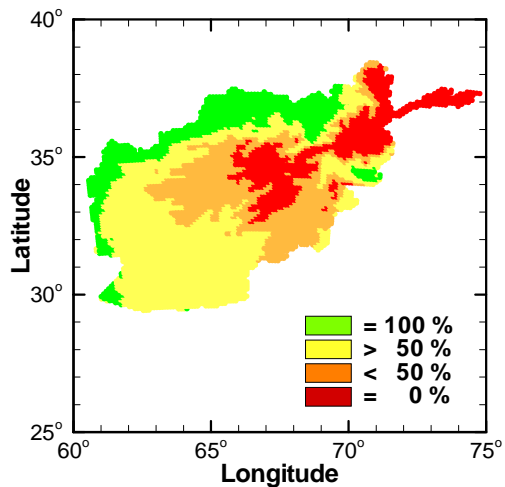

Figure 15: HOGE capability for July, based upon equivalent pressure altitude.
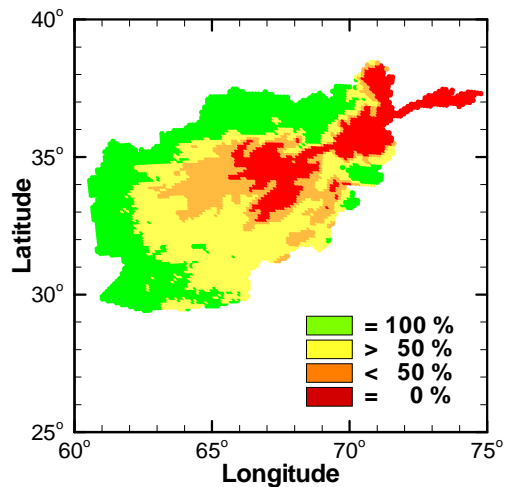

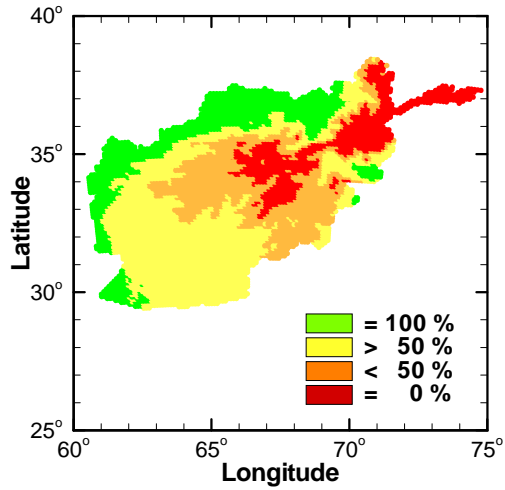**Figure 18: HOGE capability for July, based upon geophysical elevation.**

Figure 19: HOGE capability for August, based upon equivalent pressure altitude.
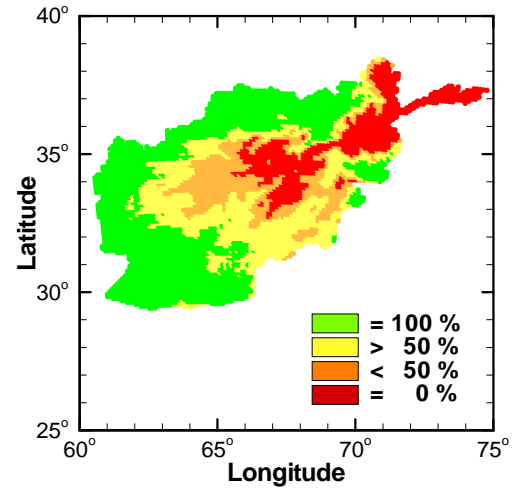

Figure 22: HOGE capability for August, based upon geophysical elevation.

Figure 20: HOGE capability for September, based upon equivalent pressure altitude.

Figure 23: HOGE capability for September, based upon geophysical elevation.

Figure 21: HOGE capability for October, based upon equivalent pressure altitude.

Figure 24: HOGE capability for October, based upon geophysical elevation.

Figure 25: HOGE capability for November, based upon equivalent pressure altitude.

Figure 27: HOGE capability for November, based upon geophysical elevation.
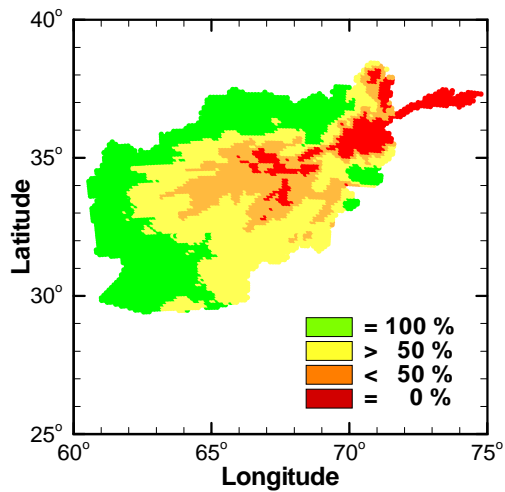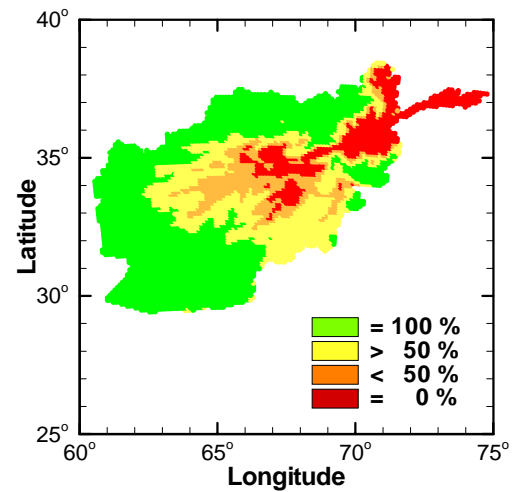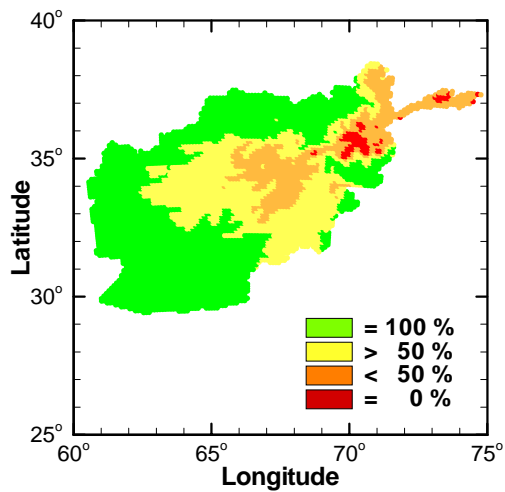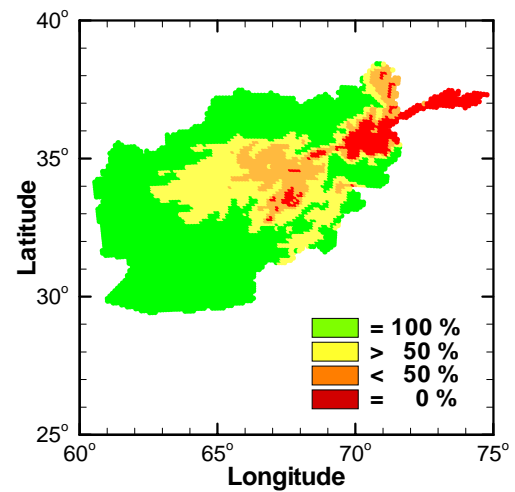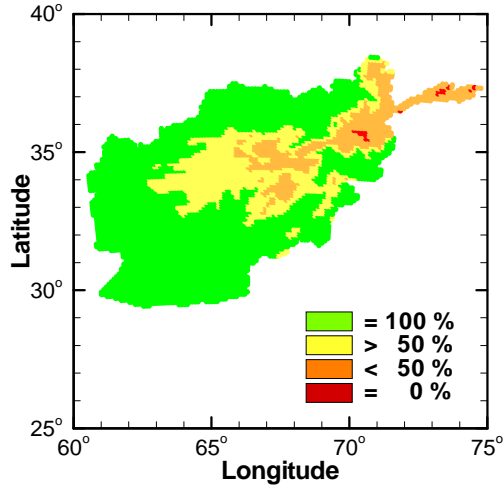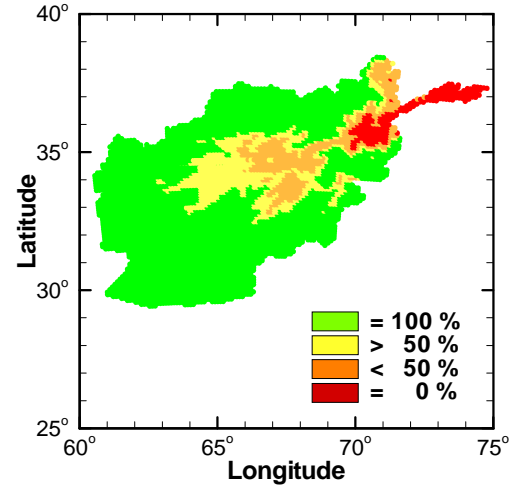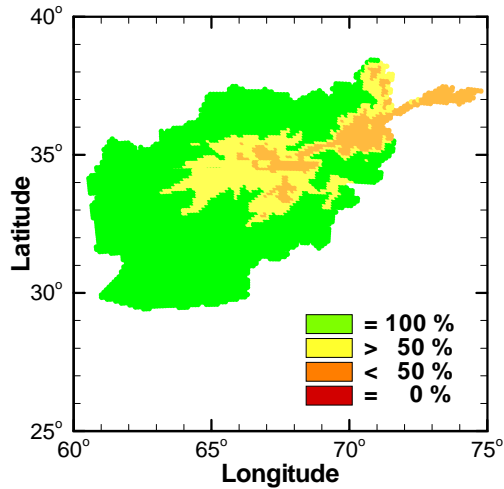

Figure 26: HOGE capability for December, based upon equivalent pressure altitude.
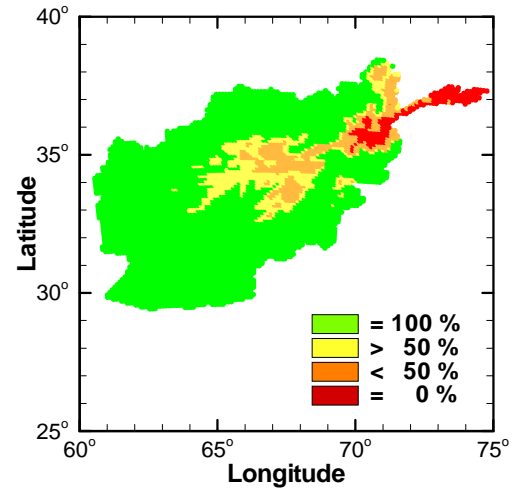
Figure 28: HOGE capability for December, based upon geophysical elevation.

Table 1: Monthly cumulative probabilities of HOGE for the mean maximum, mean average and mean minimum temperature data sets.

Month	Maximum		Average		Minimum	
	Press. Alt.	Geo. Elev.	Press. Alt.	Geo. Elev.	Press. Alt.	Geo. Elev.
Jan	76	82	95	93	100	97
Feb	73	81	91	90	100	97
Mar	61	72	88	88	100	97
Apr	52	61	84	85	99	96
May	37	53	76	80	96	95
Jun	15	39	65	72	88	87
Jul	15	34	60	69	85	85
Aug	19	44	62	71	86	86
Sep	38	53	74	77	92	89
Oct	56	64	85	85	99	94
Nov	68	74	89	87	100	96
Dec	74	79	91	89	100	97

The columns under the 'Minimum' heading were calculated from minimum mean temperature data, the columns under the 'Average' heading were calculated with the mean average temperature data, and the columns under the 'Maximum' heading were calculated with the mean maximum temperature data. Therefore, the 'Minimum' column probabilities indicate the fraction of the maps that are not colored red, the 'Average' numbers are the fraction contained within the green and yellow colors, and the 'Maximum' figures are the fraction colored green.

The probabilities under the 'Press. Alt.' subheading were calculated using equivalent pressure altitude, therefore they correspond to odd-numbered Figures 5 through 27. The probabilities under the 'Geo. Elev.' subheading were calculated using geophysical elevation; therefore they correspond to even-numbered Figures 6 through 28.

It may be noticed from Table 1 that the largest values for probability of HOGE are located within the 'Minimum'' columns. This is result of the fact that the probability of HOGE is inversely proportional to temperature and altitude, so the maximum probability occurs for the combination of mean minimum pressure altitude and minimum mean temperature for the values computed using pressure altitude. Conversely, the lowest probability of HOGE occurs for the combination of mean maximum pressure altitude and mean maximum temperature. HOGE capability is only dependant on temperature for the values computed using geophysical elevation.

By studying the figures and the table, it may be seen that the use of equivalent pressure altitude in estimating HOGE tends to reduce the areas of the lowest HOGE probabilities, to increase the areas of the highest HOGE probabilities, and to expand the areas of the intermediate HOGE probabilities, as compared to the maps based on geophysical elevation. The largest difference is seen in the decrease in the areas of 100 percent probability of HOGE from the geophysical elevation based plots to the equivalent pressure altitude based plots. During the hottest months of the year (June, July, and August), the pressure altitude based plots indicate that areas where unconditional HOGE is possible is slightly under half the size of the areas shown in the geophysical elevation based maps.

By creating maps of HOGE capability, it is possible to visualize the geographic capability of a helicopter for a given region. One possible application of this methodology would be to determine the operational HOGE capability for specific locations within the region of interest over the course of a year. This is not shown by the plots of cumulative probabilities of altitudes and temperatures, such as those shown in Figures 3 and 4.

Conclusions

1. An updated methodology to evaluate a helicopter's hover out of ground effect capability has been presented. This methodology uses modern climatology models to create geographically refined data sets for use in estimating the cumulative probability of HOGE for a given region.

2. It has been shown that local pressure variations can cause equivalent pressure altitudes to differ from geophysical elevation enough to significantly affect HOGE capability estimates. Equivalent pressure altitude is a better parameter for use in estimating HOGE capability than local geophysical elevation.

3. The inclusion of mean minimum and mean maximum temperature and equivalent pressure altitude data provides a more detailed view of the annual climate cycle for a given region than is given by using the mean maximum values of those quantities. This provides a realistic overview of the trade space involved for helicopter operation in a given region.

4. Maps showing local probability of HOGE can offer greater insight into local geographical operational capability than plots showing annual cumulative probability of HOGE for a given region.

Acknowledgments

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